

Effects of masker envelope coherence on intensity discrimination

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Masked detection threshold for a pure tone signal depends on the coherence of masker envelope fluctuation across frequency, with lower thresholds for coherent fluctuation under some conditions. The benefit of coherent masker modulation is larger for detection than for suprathreshold tasks, such as pure tone intensity discrimination [Hall, J. W. and Grose, J. H. (1995). *J. Acoust. Soc. Am.* **98**, 847–852]. In the present study, sensitivity to increments in signal intensity was measured for a 1000-Hz signal, either a tone or a 20-Hz-wide narrowband noise. In one set of conditions the masker was one or more bands of noise, each 20 Hz wide, and in another set of conditions the masker was a single 1620-Hz-wide band of Gaussian noise or noise multiplied by the envelope of a 20-Hz bandpass noise. Coherent masker envelope fluctuation improved detection thresholds in all conditions. Intensity discrimination for a tonal standard in comodulated noise was elevated for standard levels near detection threshold and improved with increasing signal-to-noise ratio, whereas performance was uniformly poor across level for the noise standard. Results are most consistent with the interpretation that the reduced benefit of coherent masker modulation in suprathreshold intensity discrimination is due to the disruptive effects of envelope fluctuation.

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I. INTRODUCTION

Detection threshold for a tone in narrowband noise can be reduced with the introduction of additional off-frequency noise bands, provided those bands have the same pattern of envelope fluctuation as the on-signal masker band (Hall *et al.*, 1984). This result is sometimes described as comodulation masking release (CMR). Whereas detection thresholds improve with the introduction of coherently modulated flanking maskers, several lines of evidence indicate that masking release is smaller for suprathreshold discrimination than for detection tasks. For example, Hall and Grose (1995) reported greater masking release for detection than for intensity discrimination of a tonal signal presented at a low sensation level, a task described as suprathreshold intensity discrimination.¹ This difference in masking release was illustrated by comparing intensity discrimination thresholds for standard levels that were defined relative to detection threshold. When performance is compared across masker conditions for signals at a low sensation level (SL), such as 10 dB SL, discrimination thresholds are worse in the context of coherently modulated masker bands than in the context of one or more random noise maskers. The CMR obtained for detection is larger than that for suprathreshold discrimination across a range of tasks, including intensity discrimination (Hall and Grose, 1995), gap detection (Hall and Grose, 1992), pitch ranking (Hall *et al.*, 1997), and speech perception (Grose and Hall, 1992). Hall *et al.* (1997) hypothesized that coherent masker envelope fluctuation lowers detection threshold, but that the resulting representation of the signal is degraded, which in turn limits sensitivity in suprathreshold tasks. The purpose of the present experiments was to more

fully characterize the differential effects of coherent masker modulation on suprathreshold intensity discrimination as compared to signal detection.

In some cases threshold improvement associated with masker fluctuation coherence is attributed to an across-channel process, whereby detection of the signal is enhanced by information carried in independent auditory channels (Haggard *et al.*, 1990; Hall *et al.*, 1993; Moore *et al.*, 1993; Buss and Hall, 2008; Grose *et al.*, 2009). This process may involve a comparison of stimulus envelopes across frequency or a listening strategy whereby off-frequency modulation is used to facilitate “listening in the dips” of the masker (Buus, 1985). Hall and Grose (1995) suggested that derived detection cues, such as those based on the introduction of across-channel envelope differences, might by their very nature contain less detailed signal information than cues based solely on within-channel information. This suggestion is broadly consistent with the finding of relatively poor suprathreshold intensity discrimination as compared to signal detection in both the CMR and binaural masking level difference paradigms (Henning, 1991; Hall and Grose, 1995). As in the case of monaural masking release, binaural masking release is thought to be based on a comparison of stimuli falling in independent peripheral channels (in this case different ears). Hall and Grose (1995) proposed that such difference cues might result in an internal representation of the signal that is essentially different from that associated with baseline conditions, and they described this degraded representation as “coarse.”

Whereas across-channel cues are thought to underlie the masking release in many CMR paradigms, under other conditions within-channel cues may support improved detection threshold in the presence of coherently modulated maskers.

For example, in many cases the within-channel pattern of envelope beats associated with a pair of comodulated narrow bands of noise is disrupted by the addition of a pure tone signal (Schooneveldt and Moore, 1987; Berg, 1996). These within-channel cues could be more useful in detection than discrimination. Further, the proximity of flanking masker bands could interfere with the use of cues that would otherwise contribute to intensity discrimination. In general, intensity discrimination for a spectrally narrow signal tends to improve as a function of level of the standard, a result that has been described as the “near miss” to Weber’s law. It is widely accepted that this near miss is due to spread of excitation at higher stimulus levels and hence a wider range of frequency channels representing the signal (e.g., Florentine and Buus, 1981). To the extent that internal noise is independent across channels, this effect could be due to reduced effects of internal noise with multiple samples. Nonlinear growth of masking on the high frequency side of the excitation pattern may also contribute to the beneficial effects of spread of excitation (Zwicker, 1970). Whereas spread of excitation could improve intensity discrimination, masking of this spread could play a role in the relatively poor suprathreshold performance observed with coherently modulated flanking maskers. While random flanking maskers could interfere with intensity discrimination, this effect might be more pronounced in coherent masker conditions where dynamic spectral masking is synchronous above and below the signal frequency.

Variability in the stimulus level associated with masker envelope fluctuation could also play a role in suprathreshold intensity discrimination. A classic study by Bos and de Boer (1966) showed that the inherent amplitude modulation (AM) of narrowband noise stimuli limits intensity discrimination as well as sensitivity to an added tone for bandwidths of 10–40 Hz. Corroborating this result, Eddins (2001) reported lower thresholds for intensity increment detection when the standard stimulus was a low-fluctuation noise as compared to a Gaussian noise of the same narrow bandwidth, a result that confirms the effects of stimulus fluctuation independent of bandwidth. When a pure tone signal is added to a bandpass Gaussian noise it tends to flatten the envelope, with greater effects at higher signal-to-noise ratios (SNRs). Assuming that the signal and the masker band centered on the signal are spectrally resolved from flanking maskers, increasing the signal level has a uniform effect on the statistical properties of the encoded signal irrespective of the presence of flanking masker bands. To the extent that coherence of the masker envelope across frequency reduces detection thresholds, stimuli presented at a low SL (e.g., 10-dB SL) will have more pronounced envelope fluctuation in the coherent modulation as compared to the baseline conditions of the CMR paradigm. The detrimental effects of stimulus envelope fluctuation on intensity discrimination could therefore be responsible for the poor suprathreshold discrimination thresholds in coherent masker conditions.

One way to think about the disruptive effects of envelope fluctuation on intensity discrimination is in terms of the differential effects of internal and external noise (Swets *et al.*, 1959). Whereas intensity discrimination thresholds for

stationary stimuli are likely to be limited by internal noise, stimuli with an interval-by-interval level rove are limited by external, stimulus-based noise (Spiegel *et al.*, 1981; Jesteadt *et al.*, 2003). In a recent study it was argued that the poorer intensity discrimination for stimuli with fluctuating envelopes might likewise be attributable to increased external noise (Buss *et al.*, 2006). This could have implications for the utility of cues present in the auditory channel centered on the signal as well as the ability to benefit from spread of excitation. If the spread of excitation with increasing presentation level improves intensity discrimination due to a reduction in the effects of internal noise, then these beneficial effects could be more pronounced under conditions of minimal envelope fluctuation, for which internal noise limits performance, as compared to highly fluctuating stimuli, for which external noise limits performance.

Masking noise does not have to be presented synchronously with the signal to interfere with intensity discrimination. Several groups have demonstrated that intensity discrimination can be disrupted by nonsimultaneous masking noise even if that noise does not affect detection threshold (e.g., Zeng *et al.*, 1991; Carlyon and Beveridge, 1993; Plack *et al.*, 1995; Plack, 1996; Oberfeld, 2008). Intensity discrimination in nonsimultaneous masking conditions appears to be quite complex and is not fully understood (see Zeng, 1998; Oberfeld, 2008), but one possible explanation is that maskers presented before or after the signal could interfere with the trace memory representing the intensity in each interval, particularly if the masker has prominent inherent fluctuation (Plack *et al.*, 1995). In the case of intensity discrimination in the presence of coherently modulating masker bands, variability in masker level could interfere with intensity discrimination for standard tones presented near threshold by virtue of corrupting the memory trace associated with the standard. In baseline conditions, with one or more random noise maskers, this interference may be less severe because the level of the standard is closer to the peak masker level, which may serve as a perceptual reference point or anchor (Braidia *et al.*, 1984). Disruption of memory traces could also be related to the effects of modulation within the listening interval, with greater disruption under conditions for which the masker and signal-plus-masker stimuli are both highly modulated and therefore perceptually similar.

The broad goal of the experiments described in the present report was to differentiate among possible explanations for reduced masking release in suprathreshold intensity discrimination tasks. To summarize, those included (1) coarse representation of the signal due to the loss of information inherent in an across-channel comparison, (2) masking associated with flanking masker bands, (3) detrimental within-channel effects of stimulus envelope fluctuation, (4) limits on the ability to benefit from spread of excitation due to envelope fluctuation, and (5) detrimental effects of level fluctuation between intervals on memory for the standard level. A secondary goal was to replicate intensity discrimination results previously demonstrated with narrowband maskers and to determine whether similar effects are obtained with a single spectrally contiguous masker, wherein coherent AM is introduced via multiplication by a low-rate

modulator. This spectrally contiguous, multiplied masker was of interest because it more closely resembles comodulated background noise that may be encountered under natural listening conditions.

Experiment 1 measured detection and suprathreshold intensity discrimination thresholds for a pure tone signal presented in either a set of narrowband maskers or a single bandpass masker to determine the effects of coherent AM. These results establish the basic effect under study. Using just narrowband noise maskers, Experiment 2 measured detection and intensity discrimination thresholds for a narrowband noise signal. In contrast to the envelope modulation reduction as a function of SNR obtained with a tonal signal, there is pronounced envelope fluctuation irrespective of SNR when the signal is a narrowband noise. If envelope fluctuation is responsible for the level effects with a tonal signal, then discrimination with narrowband noise signals should be insensitive to level. Experiment 3 explored the relative contributions of envelope variability and spread of excitation to suprathreshold intensity discrimination measured with and without narrowband flanking masker bands.

II. GENERAL PROCEDURES

A. Observers

Observers were 15 normal hearing adults, ages 18–53 years (mean 30 years). All were screened for normal hearing in the test ear, defined as thresholds of 15-dB hearing level (HL) or better for pure tones 250–8000 Hz (ANSI, 1996). None of these observers reported a history of ear disease, and all had previously participated in psychoacoustic studies. A subset of observers completed each experiment, as indicated below.

B. Stimulus generation

The signal was either a 1000-Hz pure tone (Exp 1 and 3) or a 20-Hz-wide band of noise arithmetically centered on 1000 Hz (Exp 2). This signal was gated on and off with 50-ms raised-cosine ramps and had a total duration of 450 ms. In some cases the task was to detect the presence of a signal, while in others the task was to select the interval associated with the most intense signal. Maskers were one or more 20-Hz-wide bands of noise, a single bandpass noise, or an amplitude modulated bandpass noise.

Narrowband and bandpass Gaussian noise samples were generated in the frequency domain, with draws from a normal distribution defining the real and imaginary components within the passband. Coherently modulated narrowband maskers were generated with a single family of random draws to define corresponding components of each band, whereas random bands were generated with independent random draws. Stimuli were then transformed into the time domain with an inverse fast Fourier transform. Each masker array was composed of 2^{17} points which, when played out at 12 207 Hz, could be repeated seamlessly with one repetition every 10.7 s. The average masker presentation levels are reported separately for each experiment. Due to the random fluctuations of noise, the masker level in each listening interval deviated slightly from that mean. Maskers played con-

tinuously in Experiments 1 and 2, whereas in Experiment 3 some portions of the masker were gated on only during the listening interval. The maskers were generated in MATLAB prior to every threshold estimation run.

Stimuli were played out at 12 207 Hz (RP2, TDT), passed through a headphone buffer (HB7, TDT), and presented to the left channel of a pair of circumaural headphones (Sennheiser, HD 265).

C. Procedures

All thresholds were estimated using a three-alternative forced-choice procedure and a three-down one-up tracking rule estimating 79% correct (Levitt, 1971). In all cases the masker was held at a constant level over the course of a track, and the level of the signal was adjusted. For the detection task signal level was defined in units of dB SPL, and in the intensity discrimination task the signal was defined in units of $10 \log(\Delta I/I)$. For both detection and intensity discrimination tasks the initial signal level adjustments were made in steps of 4 dB, and steps were reduced to 2 dB after the second track reversal. A total of eight reversals was obtained in each track, and the threshold estimate was the average signal level at the last six track reversals.

In the detection task the observer was presented with three listening intervals, each 450 ms in duration and separated by 300-ms interstimulus intervals. Each listening interval was visually indicated with a light mounted above the associated response button on a handheld response box. The signal was presented in one of these intervals with equal probability, and the observer indicated which interval contained the signal; visual feedback was then provided. In the discrimination tasks the procedures were identical except that there was a standard stimulus in all three intervals, and the observer's task was to select the interval in which the level of that standard was incremented. For intensity discrimination in Experiments 1 and 2, the level of the standard was set relative to each observer's detection threshold in each condition: standard levels were either 10, 20, or 30 dB SL. Standard levels for Experiment 3 were uniform across observers, spaced at 10 dB increments between 50 and 80 dB SPL. Detection thresholds were measured prior to discrimination thresholds in Exp 1 and 2; aside from that constraint, conditions were completed in random order within an experiment.

III. EXPERIMENT 1

The first experiment assessed intensity discrimination for a pure tone in the presence of a comodulated masker as compared to baseline conditions, with one or more bands of independent noise. In one set of conditions the masker was composed of up to five narrow bands of noise. These conditions closely resemble those of Hall and Grose (1995), where suprathreshold intensity discrimination was shown to be poorer in coherent masker conditions than in baseline conditions when comparing performance for a standard presented at a fixed level relative to detection threshold. Other conditions in the present experiment measured intensity discrimination thresholds with a single contiguous bandpass masker

TABLE I. Mean detection thresholds for each masker type examined in Experiment 1, with standard error of the mean shown in parentheses.

	Narrowband			Bandpass	
	On-signal	Random	Coherent	Gaussian	AM-noise
Primary conditions	51.8 (0.34)	51.6 (0.39)	43.0(0.98)	52.1 (0.50)	45.8(0.74)
+10-dB masker level			52.5(1.46)		55.8(0.59)

that was either Gaussian noise or AM noise. It was hypothesized that the effect of masker coherence on suprathreshold intensity discrimination for the bandpass masker would be similar to that previously shown in the narrowband masker paradigm. Such a result would lend support to the idea that the finding of poor suprathreshold discrimination in coherently modulated narrowband maskers may generalize to more natural listening conditions, such as speech masked by a spectrally contiguous fluctuating background noise.

A. Observers

Observers 1–7 participated, including four males, and the mean age in this subgroup of observers was 36 years.

B. Stimuli

The signal was a 1000-Hz pure tone, and the task was to detect the presence of a signal or an increment in the level of the signal. There were five primary masker conditions, three for which the masker was comprised of narrow bands of noise and two in which the masker was a single, spectrally contiguous bandpass noise.

In the *on-signal* masker condition there was a single 20-Hz-wide band of Gaussian noise centered on 1000 Hz. In the *random* masker condition there was a set of five 20-Hz-wide bands of Gaussian noise, centered on 200, 600, 1000, 1400, and 1800 Hz. The *coherent* masker condition included 20-Hz-wide bands at the same frequencies, but those bands were comodulated. In the primary conditions each masker band was presented at 50 dB SPL for an overall level of 57 dB SPL when all five bands were present.

There were two bandpass masker conditions, wherein the masker was filtered to span the same spectral range as maskers in the narrowband noise conditions (190–1810 Hz). In the *Gaussian* condition the masker was a band-limited Gaussian noise. In the *AM-noise* condition a bandpass Gaussian noise sample was multiplied by the Hilbert envelope associated with a 20-Hz narrowband noise, generated using procedures described above for the *on-signal* masker. Bandpass maskers were played at 65 dB SPL.

The masker levels used in the primary conditions described up to this point were chosen to produce approximately equal thresholds in the *on-signal*, *random*, and *Gaussian* baseline conditions. Thresholds were expected to be significantly lower in the *coherent* and *AM-noise* conditions, a reduction associated with introduction of coherent masker envelope fluctuation across masker frequency. In order to allow comparison of intensity discrimination across conditions at an approximately matched signal level, additional data were collected with a 10-dB higher masker level

in the two conditions associated with masking release. The *coherent*+10 condition was identical to the *coherent* condition described above, but the masker was presented at an overall level of 67 dB SPL. Similarly, the *AM-noise*+10 condition was identical to the *AM-noise* condition in all respects other than the 75 dB SPL overall masker presentation level. These levels were chosen based on pilot data indicating masking release on the order of 10 dB in both the narrowband and bandpass noise conditions.

C. Results

The pattern of results was broadly consistent across observers, so only mean results will be presented. The mean detection thresholds are reported for each masker condition in Table I. For narrowband maskers, thresholds in the two baseline conditions were quite similar, with means of 51.8 and 51.6 dB in the *on-signal* and *random* conditions, respectively. Thresholds dropped to 43.0 dB in the *coherent* condition for a masking release of approximately 8.7 dB. For bandpass maskers, thresholds in the *Gaussian* baseline condition were 52.1 dB as compared to 45.8 dB in *AM-noise* condition for a masking release of 6.3 dB. Increasing the masker level by 10 dB elevated thresholds by 9.5 dB in the *coherent* condition and by 10.0 dB in the *AM-noise* condition.

Figure 1 shows mean intensity discrimination thresholds plotted in units of $10 \log(\Delta I/I)$ as a function of the level of the standard tone relative to detection threshold. Masker conditions are indicated with symbols, as shown above each panel. Results for the primary narrowband noise conditions appear in the far left panel (A). In the *on-signal* and *random*

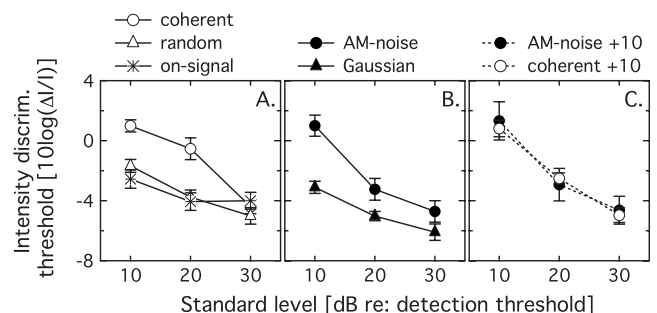


FIG. 1. Mean intensity discrimination thresholds for a pure tone signal are plotted as a function of standard level relative to detection threshold. Error bars indicate ± 1 standard error of the mean across the seven observers. Symbols reflect the masker condition, as indicated above each panel. The left panel (A) shows thresholds in the narrowband masker conditions. The middle panel (B) shows bandpass masker results. The far right panel (C) shows thresholds in the two conditions with comodulated maskers played at an increased masker level to approximately counteract masking release.

conditions, thresholds improve by an average of 2.4 dB between 10 and 30 dB SL. In contrast, thresholds in the *coherent* condition improve by 5.4 dB over the same range, converging with the other two conditions at the 30-dB SL standard level. A similar pattern is seen in the primary bandpass masker conditions shown in the middle panel (B). Thresholds in the *Gaussian* noise masker improved by approximately 3.0 dB between 10 and 30 dB SL, whereas those in the *AM-noise* improved by 5.7 dB over that range. Thresholds for the coherent masker conditions with the elevated masker level are shown in the far right panel (C). As in the primary conditions, thresholds in both the *coherent*+10 and *AM-noise*+10 conditions were elevated relative to the no-release conditions at the lowest standard level of 10 dB SL (as illustrated in panels A and B) and converged toward no-release performance with increasing standard level; thresholds in these conditions improved by an average of 5.9 dB between 10 and 30 dB SL. These results indicate that absolute signal level was not responsible for the masker effects noted in the primary data.

Intensity discrimination thresholds in the narrowband noise masker conditions were submitted to a repeated-measures analysis of variance (ANOVA) with three levels of MASKER (*coherent*, *random*, and *on-signal*) and three levels of STANDARD (10-, 20-, and 30-dB SL). There was a main effect of MASKER ($F_{2,12}=33.37, p<0.0001$) and of STANDARD ($F_{2,12}=46.30, p<0.0001$), as well as a significant interaction ($F_{4,24}=6.88, p<0.001$). Preplanned contrasts indicate that the MASKER-by-STANDARD interaction was significant comparing just the *coherent* and *random* conditions ($p<0.01$), but not when comparing the *random* and *on-signal* conditions ($p=0.06$). These results confirm the elevation of intensity discrimination thresholds in the *coherent* condition at the lowest standard level, with reduced masker effects at higher signal levels.

A similar analysis was performed with intensity discrimination thresholds in the bandpass masker conditions, with two levels of MASKER (*AM-noise* and *Gaussian*) and three levels of STANDARD (10-, 20-, and 30-dB SL). There was a main effect of MASKER ($F_{1,6}=25.13, p<0.005$) and of STANDARD ($F_{2,12}=54.44, p<0.0001$) as well as a significant interaction ($F_{2,12}=9.68, p<0.005$). These results confirm that the improvement in intensity discrimination with increasing standard level in dB SL is not uniform across *Gaussian* and *AM-noise* masker types, a result which parallels the narrowband masker results.

The effect of lower absolute level of the standard tone in the coherent masker conditions was assessed with a third analysis. This repeated-measures ANOVA included two levels of MASKER (*coherent* and *AM-noise*), two levels of LEVEL (primary and +10 dB), and three levels of STANDARD (10-, 20-, and 30-dB SL). There was a main effect of STANDARD ($F_{2,12}=95.50, p<0.0001$), but no effect of MASKER ($F_{1,6}=0.33, p=0.59$) or LEVEL ($F_{1,6}=1.52, p=0.26$). There was a significant interaction between STANDARD and MASKER ($F_{2,12}=5.05, p<0.05$), reflecting the trend for thresholds to be 0.4 dB lower in the bandpass than narrowband masker conditions. No other interactions were significant ($\alpha=0.05$). These results confirm the

visual impression that increasing masker level, and therefore signal threshold, does not substantially change the pattern of intensity discrimination as a function of standard level relative to detection threshold for these stimuli.

D. Discussion

The coherent masker results of Experiment 1 replicate the general findings of Hall and Grose (1995), where suprathreshold intensity discrimination was shown to be poorer in comodulated narrowband noise maskers than in baseline conditions when compared as a function of signal level relative to detection threshold (dB SL). This result generalized to a single contiguous bandpass noise masker, with better suprathreshold intensity discrimination for a low-SL tone in a Gaussian noise masker than in a noise that was amplitude modulated via multiplication with the envelope of a 20-Hz-wide bandpass noise. The pattern of intensity discrimination thresholds was insensitive to a 10-dB increase in masker level, indicating that suprathreshold performance in the primary conditions was not due to the lower absolute level of the standard tones in masking release conditions. Plotting thresholds as a function of level in dB SL highlights the difference between coherent modulation and baseline conditions. As also noted by Hall and Grose (1995), this difference would be deemphasized by plotting thresholds as a function of SNR. This observation on the importance of units in the comparison of intensity discrimination thresholds across masker conditions is revisited in discussion of the third experiment.

IV. EXPERIMENT 2

Intensity discrimination is poorer for a stimulus that fluctuates randomly in amplitude than for one with a more steady envelope (Bos and de Boer, 1966; Eddins, 2001). When a tone is added to a band of noise, the envelope of the summed stimulus becomes flatter with increasing intensity of the tone. In Experiment 1, intensity discrimination was compared across masker conditions at a low sensation level. Because detection thresholds were higher in baseline than in coherent masker conditions, this resulted in higher standard levels and more envelope flattening in baseline conditions. Therefore, lower signal levels and greater envelope fluctuation in the coherent masker conditions of Experiment 1 could play a role in the relatively poor intensity discrimination and reduced suprathreshold masking release.

Experiment 2 used narrowband noise maskers and examined the role of stimulus fluctuation in suprathreshold intensity discrimination by measuring intensity discrimination for a narrowband noise signal. Because this signal is itself associated with inherent amplitude modulation, the envelope of the masker-plus-signal does not become flatter at increasing SNRs. If level variability of the summed stimulus limits intensity discrimination with a pure tone signal, then signal level should have little or no effect on performance for the narrowband noise signal, and intensity discrimination should be comparably poor across baseline and masking release conditions.

TABLE II. Mean detection thresholds for each masker type examined in Experiment 2, with standard error of the mean shown in parentheses.

On-signal	Random	Coherent-ran	Coherent-copy
54.0 (0.75)	58.3 (1.05)	40.9 (0.99)	49.1 (0.90)

A. Observers

Six observers participated in this experiment, including Obs 6 and Obs 8–12. There were two males in this group, and the mean age was 24 years.

B. Stimuli

The signal was a 20-Hz-wide band of Gaussian noise arithmetically centered on 1000 Hz. There were three masker conditions, identical to the *on-signal*, *coherent*, and *random* narrowband noise conditions described above for Experiment 1. Each masker band was presented at 50 dB SPL for an overall level of 57 dB SPL when all five bands were present. In the primary conditions the signal band was a copy of the masker centered on 1000 Hz, to which it was added. In an additional condition the signal was a random band, independent of the masker band to which it was added, and all maskers were coherently modulated; this condition will be referred to as *coherent-ran* to distinguish it from the *coherent-copy* condition, where the signal was a copy of the masker band. Whereas the pattern of modulation across frequency is unchanged with addition of the signal in the *coherent-copy* condition, envelope coherence is reduced by addition of a signal in the *coherent-ran* condition. These conditions allow an assessment of the importance of across-frequency envelope coherence for suprathreshold intensity discrimination.

C. Results

Detection thresholds for the narrowband noise signal are reported in Table II. In contrast to the results of Experiment 1, thresholds were lower in the *on-signal* than in the *random* condition, with means of 54.0 and 58.3 dB, respectively. This 4.3-dB difference was significant ($t_5=5.38, p<0.005$). Thresholds in these conditions exceeded those measured under analogous conditions with a pure tone signal in Experiment 1 (as reported in Table I) for both the *on-signal* (2.2 dB; $t_{11}=2.83, p<0.05$) and the *random* (6.7 dB; $t_{11}=6.43, p<0.0001$) conditions. Thresholds improved to 40.9 dB with inclusion of coherently modulated flanking masker bands in the *coherent-ran* condition, comparable to the 43.0-dB threshold for a pure tone in Experiment 1 ($t_{11}=1.52, p=0.16$). Masking release in the *coherent-ran* condition was 13–17 dB, depending on choice of baseline. Sensitivity was not as good in the *coherent-copy* condition, where the mean threshold was 49.1 dB, and the corresponding masking release was 5–9 dB.

Figure 2 shows mean intensity discrimination thresholds plotted in units of $10 \log(\Delta I/I)$ as a function of the level of the standard relative to the corresponding detection threshold. Following the conventions of Fig. 1(A), masker conditions are indicated with symbols. Notice that whereas the

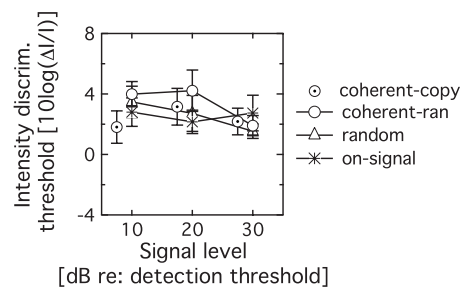


FIG. 2. Mean intensity discrimination thresholds for a narrowband noise signal are plotted as a function of standard level relative to detection threshold. Error bars indicate ± 1 standard error of the mean across the six observers. Symbols reflect the masker condition, as indicated in the legend. The dotted circles, corresponding to the *coherent-copy* condition, where the signal is an exact copy of the on-signal masker to which it is added, have been shifted leftward on the abscissa to improve resolution of points.

ordinate scale has been maintained across Figs. 1 and 2 (2 dB/div), the range of ordinate values is shifted up by 4 dB in Fig. 2. The bulls-eye symbols representing thresholds in the *coherent-copy* condition have been offset to the left to improve visual resolution of the data pattern. The most notable aspect of these results is the relative stability of thresholds as a function of standard level and the similarity of results across masking conditions. All means fall in the range of 1.5–4.2 dB, greater than the pure tone intensity discrimination thresholds for the comparable conditions of Experiment 1. Mean thresholds across all four conditions are 3.0 dB at 10-dB SL, 3.1 dB at 20-dB SL, and 2.1 dB at 30-dB SL, consistent with a small (~ 1 -dB) improvement in performance with increasing standard level.

These discrimination data were analyzed in two stages. The first stage assessed the pattern of results for the *coherent-ran*, *on-signal*, and *random* conditions. The *coherent-ran* condition was selected for this analysis for two reasons. First, the masking release was greater in this condition as compared to the *coherent-copy* condition, so any effects associated with masking release would plausibly be larger for this condition. Second, addition of the signal in this condition introduces across-frequency envelope differences, as it does for the pure tone stimulus used in Experiment 1; it was reasoned that an analysis of masker effects using this masking release condition would therefore be more comparable to previous results. A repeated-measures ANOVA was performed with three levels of MASKER (*coherent-ran*, *on-signal*, and *random*) and three levels of STANDARD (10-, 20-, and 30-dB SL). This analysis resulted in a main effect of STANDARD ($F_{2,10}=6.13, p<0.05$), no effect of MASKER ($F_{2,10}=2.59, p=0.12$), and no interaction ($F_{4,20}=1.25, p=0.32$). A preplanned contrast comparing the effect of standard level on intensity discrimination thresholds in the *coherent-ran* condition as compared to the *on-signal* and *random* conditions was not significant ($F_{1,5}=0.85, p=0.40$). These findings are consistent with the summary statement that thresholds tend to improve modestly with increasing stimulus level, and that this trend does not differ reliably across conditions associated with masking release (*coherent-ran*) and baseline conditions (*on-signal* and *random*).

The second analysis performed on the intensity discrimination data from Experiment 2 was a repeated-measures ANOVA with two levels of MASKER (*coherent-ran* and *coherent-copy*) and three levels of STANDARD (10-, 20-, and 30-dB SL). This analysis resulted in a main effect of MASKER ($F_{1,5}=12.67, p<0.05$). Both the main effect of STANDARD ($F_{2,10}=2.91, p=0.10$) and the interaction ($F_{2,10}=2.92, p=0.10$) failed to reach significance. This outcome indicates that whereas intensity discrimination thresholds were lower in the *coherent-copy* as compared to the *coherent-ran* condition, there was no statistical evidence of a differential effect of signal level across these conditions.

D. Discussion

Signal detection thresholds in the *on-signal* and *random* baseline conditions were elevated relative to those observed in comparable conditions of Experiment 1. This is consistent with the idea that observers were using features of the envelope statistics to detect a pure tone added to a narrowband of noise in the previous experiment. For example, Richards (2002) argued that both increased overall intensity and envelope flattening of the summed stimulus can contribute to sensitivity to a pure tone in a narrowband noise masker. Also in contrast to the results of Experiment 1, thresholds in these two baseline conditions differed significantly, with poorer performance in the *random* as compared to the *on-signal* conditions. While the reason for this difference is not clear, it suggests that there may be greater energetic masking or across-channel masking (Moore *et al.*, 1990; Buss, 2008) due to the flanking bands for a narrowband noise as compared to a tonal signal, perhaps due to the availability of envelope cues in tone detection.

Coherent masker envelope fluctuation improved detection relative to baseline thresholds for both the *coherent-copy* and *coherent-ran* conditions, with greater masking release for the random noise-band signal. This could be related to the fact that addition of the narrowband noise signal introduced an across-frequency envelope difference in the *coherent-ran* but not the *coherent-copy* conditions. In the latter condition the signal increased the relative level of the band at the signal frequency, but that band was still comodulated with the flanking maskers. Whereas the masking release observed under conditions of coherent masker fluctuation is often discussed in terms of the across-frequency envelope decorrelation associated with addition of a signal (Richards, 1987; van de Par and Kohlrausch, 1998), there is also precedent in the literature for obtaining a masking release in the absence of across-channel envelope decorrelation (Green and Nguyen, 1988; Hall and Grose, 1988).

Perhaps the most interesting aspect of the present data is the relative lack of an effect of standard level on intensity discrimination across all four masker conditions. Thresholds in Experiment 2 improved approximately 1 dB between 10 and 30 dB SL; in contrast, comparable pure tone data of Experiment 1 indicate an improvement of 2.4 dB in baseline conditions and 5.4 dB in masking release conditions. The finding of comparable intensity discrimination in baseline and masking release conditions for the narrowband noise sig-

nal indicates that masking release is not always associated with elevated suprathreshold discrimination thresholds. Whereas detection thresholds were 4.3 dB higher in the *random* than the *on-signal* masker conditions, consistent with masking associated with the introduction of flanking bands, intensity discrimination was not affected by the presence of flanking maskers. This finding fails to support the idea that masking more adversely affects intensity discrimination than detection.

The results of Experiment 2 are consistent with the hypothesis that the improvement observed with increasing level of a pure tone standard is due primarily to flattening of the temporal envelope of the summed stimulus, with reductions in envelope fluctuations supporting greater sensitivity to intensity changes across listening intervals. The finding of a small improvement in thresholds with increasing standard level of the narrowband noise signal could reflect a modest additional beneficial effect of spread of excitation. These results are also broadly consistent with the idea that stimulus fluctuation disrupts memory for intensity, an effect that may be more pronounced when the masker and signal-plus-masker are perceptually similar.

V. EXPERIMENT 3

The results of Experiment 2 are consistent with the idea that stimulus amplitude fluctuation plays an important role in the ability to discriminate intensity of a suprathreshold signal. In that paradigm the envelope modulation depth of the on-signal masker band summed with the signal itself does not depend on the SNR; for these stimuli, fluctuations conform to the envelope statistics of a 20-Hz band of Gaussian noise for all SNRs. The relatively poor intensity discrimination thresholds in all conditions of Experiment 2 (see Fig. 2) are consistent with the idea that performance is poor when the standard is characterized by marked envelope fluctuation, even as the level of the standard increases. Despite this, there was a slight but significant improvement in intensity discrimination as a function of level, an effect of about 1-dB improvement in threshold with a 20-dB increase in the standard level. This result suggests that absolute level could play a small but significant role in performance under conditions of pronounced stimulus fluctuation. The third experiment was designed to further assess the role of envelope fluctuation and absolute level in the improved intensity discrimination with increasing level of a pure tone standard, such as that observed in the data of Experiment 1.

Increasing the SNR of a pure tone signal in a narrowband noise has at least two effects: it tends to reduce inherent fluctuations of the signal/masker sum, and it also increases the opportunity to benefit from representation of the signal in multiple auditory channels due to spread of excitation. These two effects might not be mutually exclusive. Whereas intensity discrimination thresholds for stationary stimuli are likely to be limited by internal noise, thresholds for stimuli with fluctuating envelopes might be limited by external noise (Buss *et al.*, 2006). If the near miss to Weber's law is due in part to combination of information across auditory channels with independent internal noise (Florentine and Buus, 1981),

then the effect of stimulus level on performance would be expected to depend on the degree to which internal noise (as opposed to external noise) limits performance. In this context, reduced envelope fluctuation associated with increased SNR of a pure tone signal could improve performance by reducing external noise, with this reduction improving on-frequency cues and facilitating benefit derived from spread of excitation. If factors related to the reduction in envelope fluctuation and spread of excitation contribute synergistically to level effects in suprathreshold pure tone intensity discrimination, then spread of excitation would have a smaller effect in conditions where increasing level of the standard is *not* associated with reduced fluctuation. This would be consistent with the idea that the standard level effect observed in Experiment 2 was small because large amplitude fluctuations in the signal-plus-masker precluded taking full advantage of the detection benefits associated with spread of excitation.

The approach taken in Experiment 3 was to dissociate the two effects of increasing the SNR of a tonal standard added to narrowband noise. Whereas Experiment 2 incorporated highly fluctuating stimuli at a range of standard levels, Experiment 3 included stimuli with a range of envelope statistics, either with or without associated standard level increments. This approach allows a test of the hypothesis that the level effects for intensity discrimination of a tone in narrowband noise are the consequence of both absolute level effects and reduction in envelope fluctuation with increasing SNR. The procedures used to dissociate envelope and level effects of increasing SNR differ from those in previous experiments in several important respects. In conditions for which absolute level was held constant across SNR, the tonal standard and the narrowband noise masker at the signal frequency were summed and then that sum was scaled back to 50 dB SPL, the level of the *on-signal* masker alone. Another important procedural difference is that the standard and standard-plus-increment intervals differed only in the level of the summed stimulus: both the standard and the standard-plus-increment intervals contained a composite stimulus composed of a 1000-Hz tone and a narrowband masker centered on 1000 Hz, and the SNR of this composite stimulus was held constant across all intervals. The composite stimulus was gated on only during the listening intervals, analogous to the gating imposed on the pure tone standard alone in Experiment 1. In the *random* condition flanking bands were presented continuously.

Previous work has shown that asynchronous onset of maskers distributed across frequency can substantially disrupt processing characteristic of CMR (Dau *et al.*, 2004; Grose *et al.*, 2009). For that reason masker conditions in Experiment 3 were restricted to the *on-signal* and *random* masker conditions. The extent to which results in the baseline conditions generalize to coherent masker conditions will be addressed in the discussion, where data from Experiments 1 and 3 are compared.

A. Observers

Five observers participated in this experiment, including Obs 7 and Obs 12–15. There were two males in this group, and the mean age was 31 years.

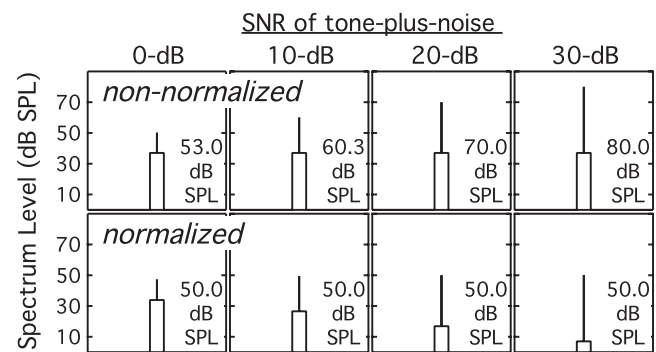


FIG. 3. Standard stimuli used in Experiment 3 are illustrated for both the *non-normalized* and *normalized* conditions and for the four values of SNR tested in each condition. The total level of the tone-plus-noise appears at the lower right of each panel.

B. Stimuli

Stimuli were based on those used in Experiment 1. The masker was either a single 20-Hz band of noise centered on 1000 Hz (*on-signal*) or a set of five bands of independent Gaussian noise centered on 200, 600, 1000, 1400, and 1800 Hz (*random*). The present experiment did not include a coherent masker fluctuation condition. The masker band centered on 1000 Hz was gated on during the listening intervals, with 50-ms raised-cosine ramps and a half-rise duration of 400 ms. In contrast, in the *random* conditions the flanking masker bands above and below the 1000-Hz frequency region played continuously. This gating manipulation was introduced to facilitate segregation of the tone and *on-signal* masker from the ongoing stream of flanking masker bands, thereby increasing confidence that any effect of flanking masker bands would be due to energetic masking as opposed to a failure to selectively attend to stimuli in the region of 1000 Hz; this manipulation has been shown to improve intensity discrimination under conditions for which best performance is supported by information in a restricted frequency region of the stimulus (e.g., Buss, 2008).

In all conditions both the standard and standard-plus-increment stimuli were generated as the sum of a 1000-Hz pure tone and a narrowband noise at the same center frequency, with SNRs of 0, 10, 20, or 30 dB. In one set of conditions the narrowband noise centered on 1000 Hz was 50 dB SPL, and the tone was 50, 60, 70, or 80 dB SPL. In a second set of conditions the composite stimuli with SNRs of 0, 10, 20, or 30 dB were scaled to a total level of 50-dB SPL in the standard intervals. These scaled stimulus conditions will be referred to as *normalized*. Idealized long-term power spectra of stimuli in the standard (no increment) intervals for these conditions appear in Fig. 3, with the total level of that portion of the stimulus centered on 1000 Hz in standard interval indicated in the lower right of each panel.

In both *normalized* and *non-normalized* conditions, the stimuli associated with standard and standard-plus-increment intervals were generated using identical procedures except that the composite stimulus was more intense in the standard-plus-increment interval. In neither case did the SNR differ across standard and standard-plus-increment intervals. These procedures allowed strict control of envelope fluctua-

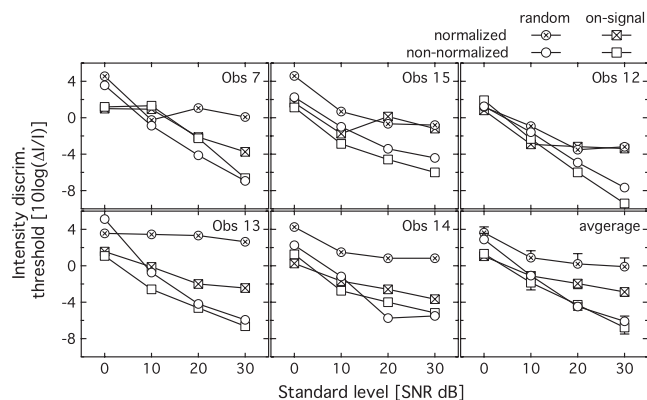


FIG. 4. Thresholds are plotted as a function of SNR, with a separate panel for each observer. The lower right panel shows the mean across observers, with error bars indicating ± 1 standard error of the mean. Symbols reflect the masker conditions, as indicated in the legend.

tion statistics across conditions and across intervals within a condition, and ensured that factors related to the detection of a change in envelope statistics did not affect intensity discrimination. As in previous experiments, intensity discrimination thresholds are reported in units of $10 \log(\Delta I/I)$. However, in the present experiment, intensity of the standard (I) and the intensity increment (ΔI) were computed based on the level of composite stimulus (signal plus 1000-Hz masker band) rather than on the pure tone alone.

C. Results

Performance varied across individuals, so thresholds for each observer are shown in Fig. 4. Thresholds are plotted in units of $10 \log(\Delta I/I)$ for a range of SNRs, and symbols reflect stimulus condition as indicated in the legend. The standard error of the mean across replicate threshold estimates within observers had a median value of 0.56 dB. The standard error of the mean across the five observers, illustrated with error bars in the bottom right panel of Fig. 4, had a median value of 0.62 dB. Initial data for Obs 7 (not shown) indicated relatively stable thresholds across conditions and across standard levels, with all thresholds falling between -2.1 and 2.0 dB. This observer was given the opportunity to practice the task, and data collection was repeated; this second set of data, shown in Fig. 4, much more closely resembles the results of the other four observers.

For most observers and in most conditions, intensity discrimination thresholds improved with increasing SNR. In the *normalized* conditions this improvement can be attributed to a reduction in amplitude fluctuation in the output of auditory filters centered at the signal frequency. In the *non-normalized* conditions there is an additional potential effect of spread of excitation due to an increased opportunity to incorporate information from a wider range of off-frequency channels. Looking across observers, thresholds tended to fall in a roughly parallel fashion in all conditions between SNRs of 0 and 10 dB. Mean thresholds improved by an average of approximately 2.4 dB in the *normalized* conditions and 3.6 dB in the *non-normalized* conditions. This result is consistent with a marked benefit of a reduction in stimulus fluctuation and little additional benefit from off-frequency cues for this

range of standard levels. For SNRs greater than 10 dB, there tends to be modest additional improvement in thresholds with increased SNR in *normalized* conditions, with average thresholds improving 1.4 dB between 10 and 30 dB SNR. In contrast, thresholds in the *non-normalized* condition continued to improve another 5.0 dB on average with further increases in SNR.

These observations of the data were assessed statistically with a repeated-measures ANOVA, with two levels of MASKER (*random* and *on-signal*), two levels of CONDITION (*normalized* and *non-normalized*), and four levels of SNR (0–30 in 10-dB steps). Significant main effects included MASKER ($F_{1,4}=15.08, p<0.05$), CONDITION ($F_{1,4}=63.04, p<0.01$), and SNR ($F_{3,12}=130.46, p<0.0001$). The CONDITION-by-SNR interaction was also significant ($F_{3,12}=23.84, p<0.0001$), but no other interaction approached significance ($p>0.10$). This result supports the observation that signal level has differential effects in the *normalized* and *non-normalized* conditions.

These results are broadly consistent with the conclusion that envelope fluctuation limits performance at low SNRs, and benefits related to spread of excitation play a role primarily at SNRs above 10 dB, where stimulus fluctuation (i.e., external noise) imposes less of a limit to performance. However, there appear to be notable individual differences in the ability to use these cues. One aspect of individual differences in these data is seen in the relationship between *on-signal* and *random* thresholds in the *normalized* stimulus conditions (filled symbols in Fig. 4). For some observers thresholds are similar in the *normalized/random* and *normalized/on-signal* conditions (e.g., Obs 12 and 15), whereas for others thresholds are consistently 2–6 dB poorer in the *normalized/random* than the *normalized/on-signal* condition (e.g., Obs 13 and 14). This difference across data sets could reflect greater susceptibility to off-frequency masking in some observers.

D. Discussion

The results of Experiment 3 are consistent with the conclusion that improved intensity discrimination with increasing level of the standard tone in Experiment 1 is dominated by reductions in amplitude fluctuation for low levels of the standard and with introduction of off-frequency cues related to spread of excitation at higher levels of the standard tone. There is sparse evidence of masking associated with the presence of flanking maskers. Overall, the thresholds were elevated 2.4 dB by the presence of random sidebands in *normalized* conditions and 0.7 dB in *non-normalized* conditions. The fact that this effect is level dependent, with slightly smaller effects in the *non-normalized* condition, is consistent with published data for off-frequency masking in intensity discrimination. Greenwood (1993) speculated that level effects for off-frequency masking could be due to the increased excitation associated with the standard “overcoming” excitation related to a neighboring masker, such that broad changes in excitation due to addition of the signal would not be fully masked. Interpretation of threshold elevation in the presence of random flanking bands in terms of energetic masking is

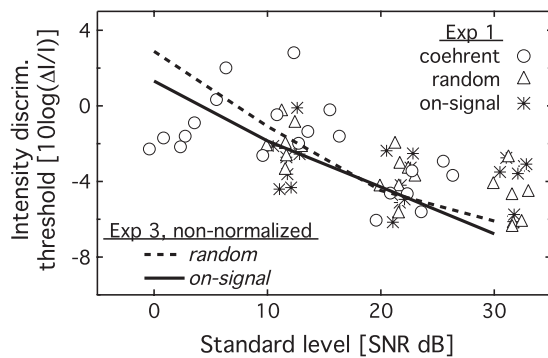


FIG. 5. Intensity discrimination thresholds in the narrowband noise conditions of Experiment 1 were recomputed relative to the level of the pure tone signal and the masker band to which it was added. The results are plotted for individual observers as a function of SNR, and symbols reflect the masker condition. The lines show mean results of the *non-normalized* conditions of Experiment 3.

undermined, however, by the finding of substantial individual differences as well as the failure to find a significant interaction between masker type (*on-signal* and *random*) and stimulus condition (*normalized* and *non-normalized*).

In contrast to Experiment 1, in the present paradigm flanking maskers were played continuously and the on-signal masker was gated on only during the listening interval, synchronously with the standard tone. This procedural difference was meant to highlight the tone and the masker in the 1000-Hz frequency region and to reduce possible confusion regarding which stimulus components are most relevant in making intensity discriminations across intervals. Another procedural difference was that the SNR was held constant across standard and standard-plus-increment intervals in Experiment 3, with intensity increments produced by a scalar applied to the tone-plus-masker composite. In order to evaluate the consistency of results obtained in these two experiments, thresholds were compared across paradigms in the following manner.

Figure 5 shows intensity discrimination as a function of standard level in dB SNR for individual observers in the three narrowband noise conditions of Experiment 1, as indicated by symbol shape. These thresholds were adjusted to incorporate the on-signal masker into the estimate of the standard level (I), similar to the approach taken in Experiment 3. This adjustment had a larger effect at the low than high SNRs, with mean reductions in threshold estimates of 2.0 dB for standard levels 0–5 dB, 0.3 dB for standard levels of 10–15 dB, and smaller effects at higher standard levels. Lines in Fig. 5 indicate mean thresholds in the *non-normalized/random* (dashed) and *non-normalized/on-signal* (solid) conditions of Experiment 3. The level effects observed in the *non-normalized* conditions of Experiment 3 capture the general trends in the data of Experiment 1, including thresholds in the *coherent* condition. Interpretation of this relationship is tempered by substantial individual differences, coupled with the fact that only one observer (Obs 7) provided data in both experiments. However, the general agreement across data sets is consistent with the conclusion that suprathreshold intensity discrimination performance in coherent masker conditions is relatively poor near detection

threshold due to the detrimental effects of stimulus envelope fluctuation. There is little evidence that additional effects related to loss of signal information following across-channel comparisons (coarseness) or to the masking associated with flanking maskers.

Recall that one hypothesis regarding elevated thresholds in masking release conditions has to do with the masker fluctuation between listening intervals corrupting trace memory for the level of the tone in each listening interval. By this account, masker fluctuation between listening intervals is more disruptive for a tonal signal played at a low SNR, perhaps due to perceptual similarity between the masker and signal-plus-masker stimuli. Data for comparable continuous and gated masker conditions were collected for the on-signal masker in Experiments 1 and 3, respectively. While there are large individual differences, mean thresholds for the continuous and gated masker are quite close for the lower two signal levels. At the highest signal level thresholds for the continuous masker conditions (Fig. 5, stars) are approximately 2 dB greater than those in the analogous gated masker condition (Fig. 5, solid lines). It is unclear whether to attribute this difference to individual variability or the effect of fixing SNR across intervals or to a reliable difference between gated and continuous masker presentation, but in any either case this pattern of results fails to support an effect of masker variability in the intertrial interval via corruption of a trace memory for level, where the largest effects would be predicted for the low rather than high signal levels.

VI. GENERAL DISCUSSION AND CONCLUSIONS

The present set of experiments was carried out to further understand intensity discrimination under conditions of masking release due to masker envelope coherence. As previously demonstrated, suprathreshold intensity discrimination for pure tone signals presented near threshold was poorer under coherent masker conditions than in baseline masking conditions at comparable levels relative to detection threshold (dB SL). Experiment 1 showed that similar suprathreshold effects can be demonstrated for both narrowband and bandpass noise masking release paradigms: in the first case masker envelope coherence is based on inherent modulation of narrowband noise maskers, and in the second case it is based on multiplication with the envelope of an independent narrowband noise. Additional control conditions confirmed that this suprathreshold deficit was not dependent on absolute signal level in either masking release paradigm. Experiment 2 showed that intensity discrimination was uniformly poor irrespective of masker condition when the signal was a narrow band of noise rather than a pure tone, consistent with the interpretation that inherent fluctuation may limit intensity discrimination for an increment added to a fluctuating standard. The final experiment assessed the relative contribution of envelope modulation reduction and increasing spread of excitation in the finding of improved intensity discrimination thresholds with increasing SNR for a pure tone standard. It was also hypothesized that spread of excitation could improve performance, particularly in combination with reduced envelope fluctuation at higher SNRs. The

results of Experiment 3 were characterized by individual differences, but were broadly consistent with a beneficial effect of reduced envelope fluctuation for relatively low SNRs. Spread of excitation appeared to contribute primarily at the higher SNRs. The presence of random flanking maskers elevated thresholds by a few decibels in some observers. However, the nonuniformity of this effect across observers and the small average effect size suggest that energetic masking of upward spread of excitation plays a minor role in the pattern of suprathreshold intensity discrimination with coherent maskers.

Taken together, results are consistent with the conclusion that level fluctuation of the stimulus components at the signal frequency, the sum of the narrowband masker and the signal, interferes with intensity discrimination in a comparable fashion across masker conditions. This effect is most evident in the coherent modulation as compared to baseline conditions when results are plotted as a function of the SL of the standard. Plotting the results in absolute signal level or SNR, as in Fig. 5, illustrates the approximate uniformity of level effects across masker conditions.

The present data suggest that the disruptive effects of inherent stimulus fluctuation within the listening interval is the most parsimonious explanation for the poor suprathreshold intensity discrimination performance observed in the presence of comodulated narrowband noise maskers, both in the present experiments and in the published data (Hall and Grose, 1995). There was no indication that derived cues based on across-frequency comparisons were less informative regarding intensity of the signal than cues in the baseline conditions. Whereas flanking maskers may elevate detection thresholds, particularly in Experiment 2, there was little evidence that masking is responsible for the reduced masking release for discrimination. Minimal data on gated as compared to continuous presentation of an on-signal masker presented alone cast doubt on the idea that masker fluctuation between listening intervals plays a role in the present results. Results of the final experiment indicate that envelope stimulus fluctuation associated with increasing SNR of a pure tone signal may reduce thresholds by improving the quality of cues at the signal frequency and by increasing the ability to benefit from spread of excitation, both effects related to reduced external noise.

It is interesting to speculate that similar factors could be responsible for the poor suprathreshold intensity discrimination observed under conditions of monaural and binaural masking release (Henning, 1991). Stimuli composed of a tonal standard in noise would be associated with greater envelope fluctuation at low than high SNR for binaural as well as monaural presentation. It is also possible that increased external noise associated with stimulus fluctuation could contribute to the finding of relatively poor gap detection for a tonal carrier presented at a low SNR in a narrowband noise background (Hall and Grose, 1992). As in intensity discrimination, stimulus envelope fluctuation is associated with poor gap detection (Shailer and Moore, 1983; Eddins *et al.*, 1992). Results of the present experiments could also be related to the finding of relatively poor suprathreshold pitch ranking for tones presented in comodulated noise (Hall *et al.*, 1997).

Perceived pitch is affected by stimulus level (for a review, see Jesteadt and Neff, 1982), so it is possible that envelope fluctuation of a tone-plus-masker could introduce variability in perceived pitch. This possibility is the topic of current research.

Reduced sensitivity in suprathreshold discrimination tasks for a signal masked by a coherently fluctuating noise is of theoretical interest in understanding basic psychoacoustic findings (e.g., CMR), but it may also be relevant the ability to process auditory stimuli under more natural listening conditions. In normal-hearing listeners, masking of a speech signal in noise can be reduced by the introduction of masker level fluctuation, with the biggest effects for relatively slow rates of modulation (Miller and Licklider, 1950; Bacon *et al.*, 1998). It has been argued that this result can be explained in terms of the reduced masker level in the modulation minima, associated with brief “glimpses” of the signal at an improved SNR (Dirks and Bower, 1970). Masker fluctuation is not as beneficial for listeners with moderate sensorineural hearing impairment as it is for normal hearing listeners (Festen and Plomp, 1990), even when controlling for the effects of audibility (Eisenberg *et al.*, 1995). Poorer temporal resolution and/or frequency selectivity in hearing-impaired listeners have been suggested to account for this result (Festen and Plomp, 1990; Baer and Moore, 1994; Eisenberg *et al.*, 1995; Bacon *et al.*, 1998), but the factors responsible for poor ability to benefit from masker level fluctuations in cochlear hearing loss are still unknown. Results of the present study with normal-hearing listeners indicate that suprathreshold intensity discrimination could also play a role in this finding.

The poor suprathreshold speech perception in amplitude modulated noise demonstrated by Grose and Hall (1992) could be affected by the fidelity with which intensity cues for speech are encoded in modulated noise. It is also likely that suprathreshold pitch discrimination and temporal processing of speech cues could limit performance on speech recognition tasks in fluctuating noise. Whereas the finding of masking release for both coherent and incoherent modulations across frequency indicates that the masking release for speech may not be closely allied with CMR (Howard-Jones and Rosen, 1993), the findings related to stimulus fluctuation at low SNRs could also apply to a wide range of conditions associated with masking release, not just those described in the CMR literature. More work is needed to assess the possible role of stimulus fluctuation and suprathreshold intensity discrimination in the perception of speech in modulated noise.

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¹Here the phrase “suprathreshold” refers to the level of the standard. This use is in contrast to the work of Wojtczak and Viemeister (2008), who studied perception of suprathreshold changes in intensity, where the changes themselves were suprathreshold.

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